RANKING MODEL FOR 3D PRINTERS

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Abstract

The capabilities of desktop additive manufacturing (AM) machines were evaluated based on the ability to produce a standard component. This work also developed a model/method for evaluating and ranking AM technologies based on select criteria that can facilitate purchasing decisions. A standard part was adapted and printed on each machine, and evaluated in various ways to provide machine-specific input data for the model. The research highlights the differences between AM units and suggests a method by which to evaluate the differences. With the rapid proliferation of desktop additive manufacturing units, a quantitative ranking system was developed to rate these units so that the consumer, for example, can use this model to assist with decision making during purchase. Although the focus of the work was on desktop systems, the approach can be applied across other AM technologies.

Introduction

Additive manufacturing (AM) is the process of producing a computer-designed three-dimensional (3D) objects through addition of material in a layer by basis. While it is sometimes referred to as freeform fabrication or rapid prototyping, 3D printing is the name given to AM when used by devices that are lower in price and overall capacity [1]. Since the 1980s, AM technology was used mostly in academic or large commercial settings. However, today there is a high demand for smaller, more affordable, desktop 3D printers by small business owners and at-home users, leading to an increase in desktop system market availability. According to the Wohlers 2013 Report, there was an increase from 66 purchased desktop systems in 2007 to 35,508 in 2012 [2]. The first affordable 3D printer was the Dimension 3D machine, released by Stratasys in 2002. Despite being advertised as “low-cost,” the system was priced at approximately $30,000 [3]. In 2007, Adrian Bowyer and his team, from the United Kingdom, built the RepRap version I “Darwin.” The idea behind the RepRap project was the creation of a self-replicating system. This means that the system can print out a significant portion of its own parts, while the remaining parts come from affordable standard engineering materials and off-the-shelf parts [4]. Since then, new systems based on the RepRap model have been developed, including Ultimaker and Makerbot. Makerbot made the first commercially available desktop 3D printer, the Cupcake. They now sell the Replicator, a more modern version of their previous systems [3]. Each year, novel printer designs become available as the result of increased consumer demand and new companies exploring this technology.

Most AM systems, whether large or small, follow a similar multi-step process. First, a computer-aided design (CAD) is made using any design software that can export files in STL format. CADs can be created on the spot or they can be obtained from imaging modalities such as computed tomography scans, magnetic resonance imaging, or ultrasound [5, 6]. The STL is then processed by software used by the specific desktop system. Some software packages allow for substantial modification in build parameters while others only allow minimal changes. The build file, as it is commonly referred to, is then transferred onto the AM system and a new build can begin. A large majority of desktop 3D printers are material extrusion systems. This is an AM process in which thermoplastic material in a flowable state is selectively dispensed through a nozzle or orifice [1]. Other printers use a sheet lamination process, where sheets of material are bonded to form an object. A standard set of terms describing AM processes, which includes material extrusion and sheet lamination, are defined within the ASTM Standard F2792 – 12a [1]. This paper tests both AM technologies.

The spectrum of industries that can benefit from using AM is very broad: automotive, aerospace, biomedical, jewelry, coin, tableware, consumer electronics, home appliances, and many others [7]. Like with any other product, when a consumer purchases a 3D desktop printer, they are expecting to receive a high quality system that prints out an almost identical replica of the CAD they have created. In the past, authors have used test parts (also called benchmark parts) encompassing specific characteristics, to rank AM technologies and systems. In most cases, authors incorporated geometric features from previously designed benchmark parts while including new features they felt added strength to their design. For example, in 2012, Moylan *et al.* proposed a part that could be used to evaluate polymer and metal processes as well as a list of rules that should be followed in designing such a part [8]. Their design included features such as holes, ramps, staircases, flat surfaces, and lateral features. Many of these were also included in a design suggested by Mahesh *et al.* in 2004 [9]. They used their benchmark part to evaluate four AM polymer technologies for geometric accuracy, warpage, and surface roughness. In 2000, Zhou *et al.* published work which tested various vat photopolymerization systems (referred to as stereolithography in their work) [10]. Their design mainly included round, square, and triangular features which they used to test horizontal and vertical dimensions, roundness, sphereness, angularity, flatness, and surface roughness. Prior to them, in 1994, Childs *et al*. developed a test part to evaluate six AM systems within four different technologies [11]. In their design, they included some free-form features such as fish-shaped and a handle-like structure. While this is not an all-inclusive list of previous work in this field, it provides a good understanding of how authors design new test parts to test and compare AM systems and technologies.

Much of the benchmark work presented above was completed using the larger, commercial AM systems. Work at the W.M. Keck Center for 3D Innovation previously rated five desktop 3D systems according to cost, build time, material usage, and geometric accuracy using a benchmark design [12]. A ranking model was developed that would take the results of these factors and rank the systems from first to fifth. The objective of this paper was to design a test part that included more features of interest. Also, the ranking model was expanded to include the following factors in addition to those previously tested: model material use to total material ratio, surface roughness, linear displacement error, and tensile properties.

Materials and Methods

Test Part Design

After a thorough literature review was conducted, a final design was reached. This design, which can be seen in Figure 1, incorporated geometric shapes and features that provided important information as to the capabilities and limitations of each of the desktop 3D systems. The chosen features are listed in Table 1. Both positive and negative features were included. Positive features are those protruding above the surface of the rectangular base while negative features are those occurring below the surface. Dimensional accuracy was tested with features A-J. The square base (feature A) was used to measure the thickness of the part, which was dependent on the accuracy of each layer thickness. The positive lateral ridges (feature B) were used to measure the width of each protruding ridge while the negative ridges (feature C) were used to measure the open spaces in-between. The positive and negative descending cylinders (features D and E) were used to measure varying diameters. Each step of the staircases (features F and G) was used to obtain various values of height. The cylinders, both positive and negative (features H and I), were used to obtain the diameter of a repeating identical feature. Features J-L were used to measure other factors as noted in the table. The four ramps (feature J) were used to measure surface roughness along planes that were inclined at 10, 15, 30, and 45° as has been done in other work [12, 13]. Linear displacement error was determined by using the rectangular prisms (feature K). Finally, the tensile bar (feature L) was used to measure ultimate tensile strength of the material. Although other authors suggested including overhanging features [8] [9], it was decided not to do so as overhanging features would have required additional support material. The need for removing support material from overhanging features would introduce variability from part to part as users may remove support differently and potentially affect the measured features. The dimensions of the design can be seen in Figure 2. The letters given to each section correspond to the letters given in Figure 1.

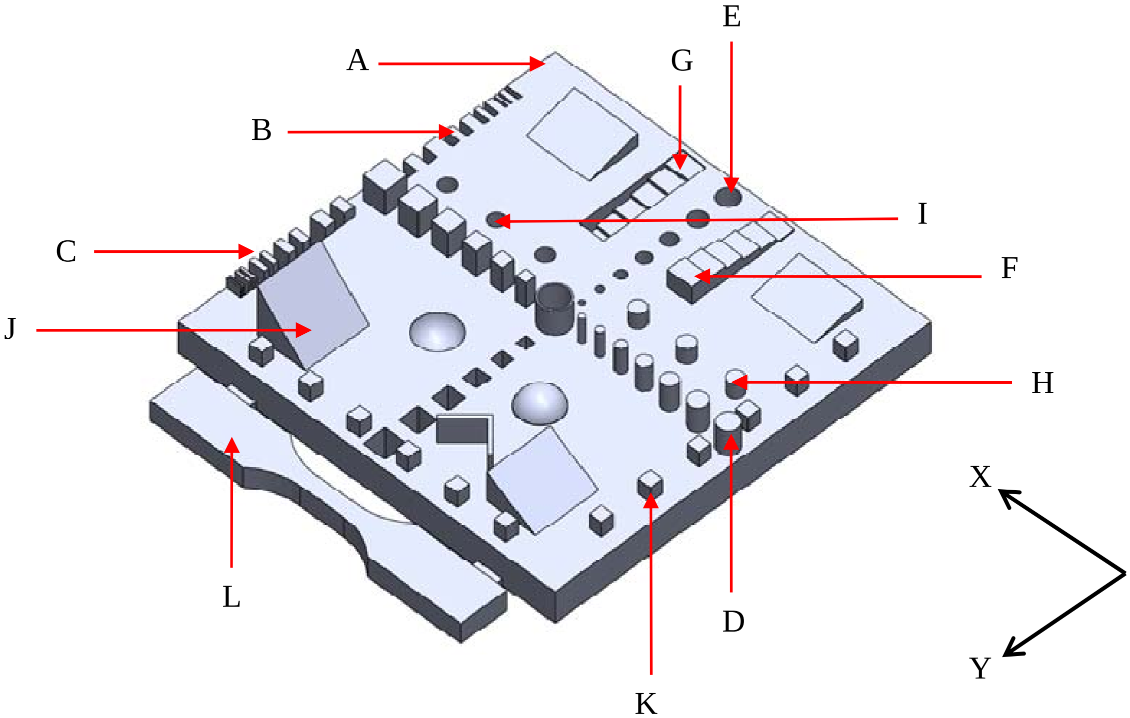


Figure 1. Design of test part used for the ranking model and the orientation in which the part was built

Table 1. Design Features of Test Part

Letter	Feature	Factor Tested
A	Square base	Dimensional accuracy
B	(+) Lateral ridges	
C	(–) Lateral ridges	
D	(+) Descending cylinders	
E	(–) Descending cylinders	
F	(+) Staircase	
G	(–) Staircase	
H	(+) Cylinders	
I	(–) Cylinders	
J	Ramps	Surface roughness
K	Rectangular prisms	Linear displacement error
L	Tensile Bar	Ultimate tensile strength

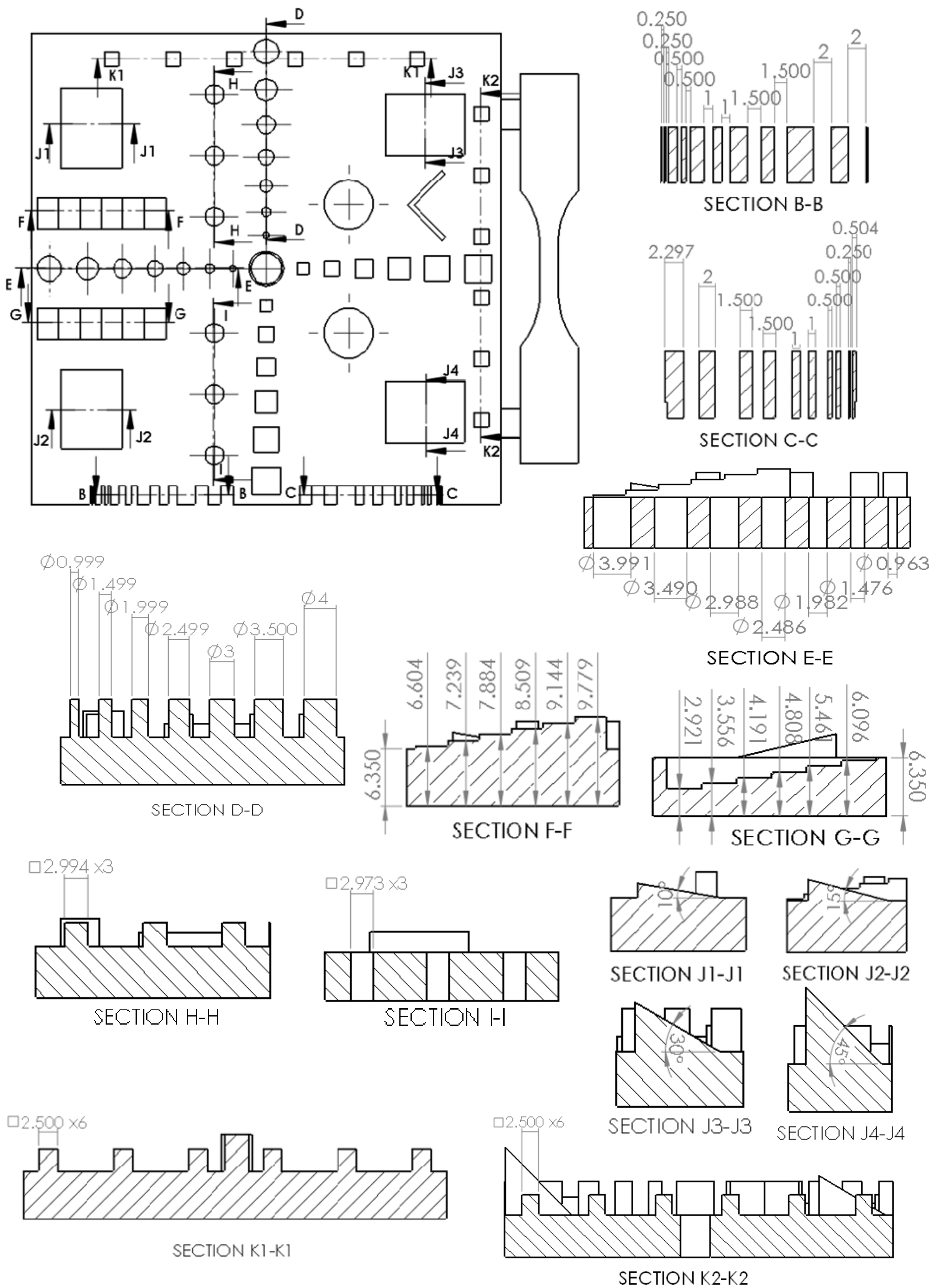


Figure 2. Design dimensions

Systems Evaluated

The desktop systems evaluated in this paper are listed in Table 2. As previously mentioned, the majority of desktop systems use material extrusion technology. Few systems use other technologies, such as the SD300 Pro which uses sheet lamination. This system is no longer sold by the original manufacturer. However, it was included in the testing presented here with the purpose of comparing results amongst different technologies and because it is still retailed by other distributers. System specifications are listed in Table 3. There are both, benefits and drawbacks, to all of the systems. Smaller systems, like the Replicator 2X which weighs 12.6 kg [14], are light enough to be transported with ease. This system, as well as the 3D Touch, works with an SD Card which also improves portability. For these reasons, these systems are well-suited for remote location and in-home use. Larger systems like the uPrint Plus, which weighs 76 kg [15], are heavier and may require two or more people to carry. Unlike the other two systems, the uPrint Plus and the SD300 Pro also require a computer connection. They may therefore, be better suited for business settings. While the uPrint is much larger and heavier than the Replicator 2X, it does not necessarily have a much larger build volume: 6264cm^3 vs. 6000 cm^3 [14, 15]. The weight difference can be largely attributed to the additional equipment included in the uPrint Plus such as the heated build envelope, material bays, and convection fans. Some may argue the uPrint Plus should not be considered a desktop 3D printer because of its high cost, over $20,000 [15]. However, it was included in these tests because it is much more compact than other commercial AM systems and may therefore, be useful in small-business settings. On the other hand, the Replicator 2X was including in this study to test if a system as affordable as this (under $3,000 [14]) could fair well against more expensive systems. Interestingly, but not necessary related, the SD300 Pro and the 3D Touch weigh the same, and are therefore, similar in price (~$4,000) [16, 17]. Three of the systems tested, the SD300 Pro, uPrint Plus, and Replicator 2X, include an enclosed build envelope (i.e. chamber surrounding the build platform). This is a safety feature that keeps the user's hands away from any moving parts during a build. The build envelopes of the uPrint Plus and the SD300 Pro can also be heated, which helps to stop the part from shrinking and warping before a build is complete [18]. This feature also improves interlayer bonding [19]. While the Replicator 2X does not have this feature, it has a heated platform that serves a similar purpose. The 3D Touch, on the other hand, is completely open. Although Bits from Bytes has discontinued this system, it was included in these tests to evaluate how the lack of a build chamber would affect the parts built. Layer thickness is another important feature because it affects the surface finish of a part. Typically, the thinner the layers, the less surface roughness present. Amongst the systems tested here, the Replicator 2X and 3D Touch have the smallest available layer thicknesses, 0.10 mm [14] and 0.125 mm [17], respectively. Some systems allow for the layer thickness to be modified, as is the case with the Replicator 2X [14] and the uPrint Plus [15].

Table 2. Systems Evaluated

System	Manufacturer	AM Technology	Headquarters
SD300 Pro	Solido	Sheet Lamination	Manchester, NH, USA
3D Touch	Bits from Bytes	Material Extrusion	Clerdon, Bristol, UK
Replicator 2X	MakerBot	Material Extrusion	Brooklyn, NY, USA
uPrint Plus	Stratasys	Material Extrusion	Eden Prairie, MN, USA

Table 3. System Specifications

System	System Dimensions (LxWxH)	System Weight	Envelope/ Build Volume	System Cost	Available Layer Thickness
	mm	kg	cm^3	USD	mm
SD300 Pro	770 x 460 x 420	36.0	4536	$4,375.00	0.168
3D Touch	515 x 515 x 598	36.0	15881	$3,930.00	0.125
Replicator 2X	490 x 320 x 531	12.6	6000	$2,799.00	0.10/0.20/0.30
uPrint Plus	660 x 635 x 787	76.0	6264	$20,900.00	0.25/0.33

Build Materials

The materials used by each system are listed in Table 4. The SD300 Pro uses polyvinyl chloride (PVC) and the material extrusion systems generally use acrylonitrile butadiene styrene (ABS). Recently, some material extrusion systems have added polylatic acid (PLA), a soluble material, to their selection. For these tests, PVC was used for the test part built with the SD300 Pro and ABS was used with the three material extrusion systems. Some desktop systems, including all the ones tested here, also have the capacity to use support material to support any overhanging features so they do not collapse before the material reaches room temperature or solidifies. Support material can be different from the model material or can be the same, but in either case is removed during post-processing. The disadvantage to using the same material for the model and support is that it may be difficult to remove without damaging the model features. The 3D Touch and Replicator 2X can also use PLA, which can be dissolved in sodium hydroxide without damaging the part. The uPrint Plus also uses a soluble support called SR-30. For this project, the initial goal was to build all of the parts without support material so as to not risk damaging the parts during support removal. However, due to the building nature of sheet lamination, PVC had to be used as support for the SD300Pro. For the 3D Touch and uPrint Plus, the raft was used (i.e. support material that separates the model material from the building platform) as it was not possible to build support-free samples with these systems. ABS was used as support by the 3D Touch and SR-30 by the uPrint Plus. Support was removed manually for all three systems. The Replicator 2X was the only system to build the test part with no support.

Table 4. Build Material Specifications

System	Model Materials Available	Model Material Cost	Support Materials Available	Support Material Cost
		USD/kg		USD/kg
SD300 Pro	PVC	$46.00	PVC	$46.00
3D Touch	ABS/PLA	$79.00	ABS/PLA	$79.00
Replicator 2X	ABS/PLA	$48.00	ABS/PLA	$48.00
uPrint Plus	ABS*plus*	$290.00	SR-30	$280.00

Build Parameters

One part was built per system using the build parameters listed in Table 5. Even though the 3D Touch and Replicator 2X allow for thinner layers to be used, the layer thickness for the three material extrusion systems was kept as constant as possible at ~0.2 mm. This was purposefully done to eliminate variables when analyzing factors like dimensional accuracy and surface roughness, both affected by layer thickness. Despite the fact layer thickness was kept constant; the number of layers each system utilized to build the part was not constant. The uPrint used the most layers of the three material extrusion systems at 74 layers. Layer thickness on the SD300 Pro cannot be modified and was, therefore, used at the factory setting of 0.168 mm. This value corresponds to the thickness of each sheet that is laid down to form a single layer. In this case, 94 sheets were used. In addition to not being able to modify the layer thickness of the SD300 Pro, the density of the part was not modifiable either. On the other three systems, the density was set as high as possible. For example, on the 3D Touch and Replicator 2X, the density was set to 100%. The uPrint Plus allows for three density settings: sparse-less dense, sparse-highly dense, and solid. Solid was chosen as it builds the densest part.

Table 5. Build Parameters

System	Layer Thickness	Number of Layers	Density Setting
	mm		
SD300 Pro	0.168	94	Not adjustable
3D Touch	0.250	65	100%
Replicator 2X	0.200	60	100%
uPrint Plus	0.254	74	Solid

Dimensional Accuracy

Dimensional accuracy was evaluated using an OGP Smartscope Flash 250 (Optical Gaging Products, Rochester, NY) equipped with a TP200 modular probe (Renishaw Inc, Hoffman Estates, IL). A series of points along the various features of the four test parts were measured with a ruby ball styli (Ø = 1 mm). The values obtained were compared to those on the original CAD of the part. A negative value indicated the feature was smaller than the CAD, whereas a positive value indicated a larger feature. For purposes of the ranking model, an absolute value was taken. The optical system on the OGP Smartscope was used to measure the negative features (i.e. holes) on the test part. These too were compared to the CAD like those obtained with the probe.

Surface Roughness

To evaluate surface roughness, a Mitutoyo SJ-201P surface roughness tester (Mitutoyo America Corp., Aurora, IL) was used. Three measurements were taken from each of the four inclined ramps. The mean Ra values of surface roughness for each ramp were added to give the test part one value for use in the ranking model. The ramps had various angles of inclination: 10°, 15°, 30°, and 45°.

Linear Displacement Error

Linear displacement error (Ϙ) in the X direction was calculated by measuring the distance (*d*) from the first rectangular prism to the second rectangular prism (See Figure 1 -

Feature K). This value was subtracted from the CAD distance and the absolute value was taken. The difference was divided by the CAD distance.

$$\text{♀} = \frac{|d_{CAD} - d_{Actual}|}{d_{CAD}}$$

The same was done for the other four rectangular prisms, always measuring the distance from the first rectangular prism, and the five values of ♀ were averaged. This was then done for the rectangular prisms in the Y direction and the X and Y values were added to obtain one linear displacement error for use in the ranking model.

Mechanical Testing

Mechanical testing was completed using the ASTM D638 Type V specimen built alongside the square base of the design [20]. An Instron 5866 (Instron, Norwood, MA) tensile testing machine with a load cell of 10 kN and a load measurement accuracy of ± 0.4% (as per manufacturer's specifications) was used to measure ultimate tensile strength. As per ASTM D638 recommendations, the specimens were conditioned at 23°C and 50% relative humidity for 40 hours.

Ranking Model

The systems were ranked based on eight equally weighted factors: build time (TF), model material use to total material use (PT), cost of the system (UC), material cost to build one part (MC), dimensional deviations between actual part and CAD (SD), surface roughness (Ra), linear displacement error (LD), and tensile testing (TT). PT was calculated by dividing the mass of the already-cleaned part by the total mass of material used (both model and support). A PT value of 1 indicated that no waste material was generated and a decrease in PT value was evidence that waste material was produced. MC was obtained by multiplying the cost per gram of material by the total mass of material (both, model and support) necessary to build the part. SD was calculated as the sum of the absolute value differences between the measured part and expected CAD dimensions. These eight factors allowed for a consistent method of comparison that removed biased evaluations such as the user-friendliness of the system. One of the benefits of the quantitative method described below is that it can be modified to include more factors or systems. The following steps were used to determine the contribution of each factor to the total score of a system:

1. The mean ($\bar{x}$) and standard deviations (s) for each data set within a factor were calculated in the following way:

$$\bar{x} = \frac{\sum x_i}{n}$$

$$s = \sqrt{\sum_{i=1}^{n} \frac{(x_i - \bar{x})^2}{n - 1}}$$

2. The following formulas were used to calculate a threshold value (ϑ):

   $\vartheta = \bar{x} + s$ [used when a low value of *x* was preferable, such as in TF, UC, MC, SD, Ra, and LD]

   $\vartheta = \bar{x} - s$ [used when a high value of *x* was preferable, such as in PT and TT]

3. Each value of *x* was compared to the threshold (ϑ) to remove outliers if

   $x_i < \vartheta$ [when a low value of *x* was preferable]

   $x_i > \vartheta$ [when a high value of *x* was preferable]

4. All outliers were removed by repeating steps 1-3. These outliers were not taken as a measurement error, but rather a measurement of the limitations of each system. In addition to revealing limitations in each system, the iterative process highlighted technological gaps between the two evaluated AM technologies (material extrusion and sheet lamination). The iterative process was a way of ensuring only competitive systems were rewarded while others were removed from the respective factor.

5. The remaining values were used to calculate each factor's contribution (FC).

   $FC = \frac{min(x)}{x_i}$ [when a low value of *x* was preferable]

   $FC = \frac{x_i}{max(x)}$ [when a high value of *x* was preferable]

6. The equally weighted contribution ($f(x)$) was calculated for each system.

   $f(x) = \frac{FC}{\sum FC}$

7. The weighted contribution ($f(x)$) was scaled based on the number of systems that survived the iteration process. [Example: If 3 units survived, the total number of points available for each factor was 3/4 or 0.75. If all systems survived, the number of points available for each factor was 4/4 or 1.]

8. The scaled and weighted contributions ($f(x)$) for each system were summed and divided by the sum of $f(x)$ of all four systems to determine the ranking score (R).

$$R = \frac{sum\ of\ f(x)\ for\ each\ system}{sum\ of\ f(x)\ for\ all\ systems}$$

The purpose of Step 6 was to ensure if all systems survived a specific iteration, the sum of all $f(x)$ values would be equal to 1. Step 7 guaranteed systems would not be excessively rewarded by having more points, if other systems were removed from a particular factor. For purposes of this paper, the ranking model weighs each of the eight factors equally. However, the model may be modified if the user decides to give more weight to one or more of the factors. For this, each $f(x)$ simply has to be multiplied by the weighting fraction the user feels is appropriate. The end goal is to deem Step 7 unnecessary by having enough parameters and systems to rank, even if not all parameters survive iteration.

Results and Discussion

General Observations

Images of the four printed parts can be seen in Figure 3. Figure 3 (A) displays the part printed with the SD300 Pro. The surface finish of the part appeared good, including that of the ramps. All of the edges were straight and there were no visible pores or holes that were not meant to be there. On the other hand, Many of the features on this part were not able to be measured because upon removal of the support, they broke off. For example, the descending cylinders (red outline) were given a dimensional value of 0 because they did not have the necessary height to be measured by the OGP Smartscope. In addition, some of the negative features were not measured because it was not possible to clean the waste material out. Figure 3 (B) shows the test part built with the 3D Touch. Most of the negative features were measureable because they were open all the way through. The edges seemed jagged and there was warping of the part on the bottom surface. There were also some areas where extra material was deposited in the movement of the tip from one feature to another (blue outline, indicated by arrow). The smaller squares also started to obtain a more circular shape. The surface roughness was prominent, especially on the ramps (red outline). The part built by the Replicator 2X is pictured in Figure 3 (C). The features were shaped well and the machine was able to build most of the smaller features with the exception of a few lateral ridges. There did not appear to be any residue of material left where it should not be. Slight warping of the bottom surface (red outline) was evident but it did not seem to affect the surface features. There was some porosity on the negative staircase where the system did not completely fill-in all gaps. Finally, the part built by the uPrint Plus is pictured in Figure 3 (D). The features on this part were shaped well, except for the smallest square which looked somewhat circular. All the negative descending cylindrical features were open except the smallest. Like the previous systems, not all the lateral ridges (red outline) were built successfully.

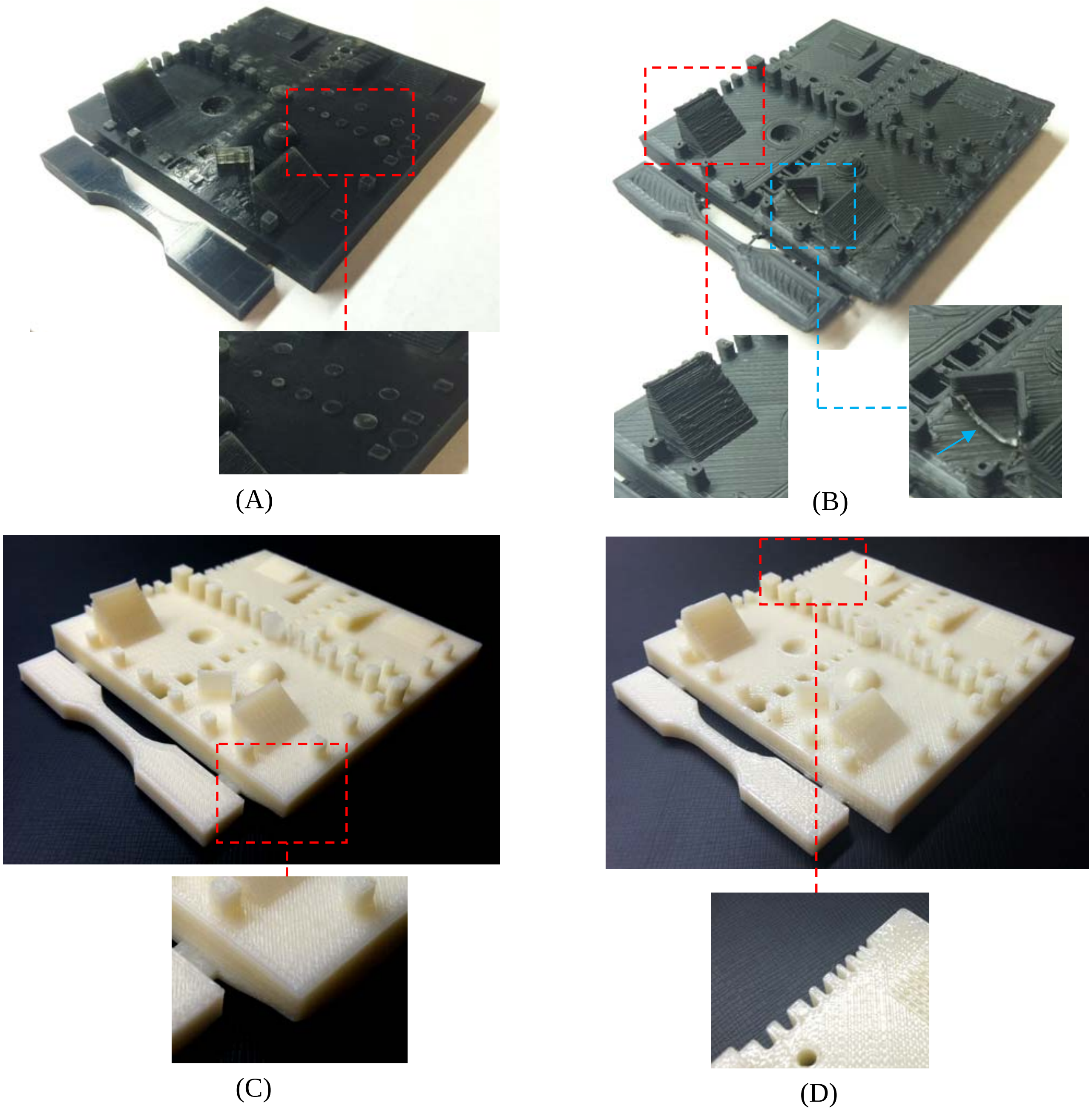


Figure 3. Test part built with the four systems: (A) SD300 Pro; (B) 3D Touch; (C) Replicator 2X; (D) uPrint Plus

Table 6 shows the results of build time and material use. The 3D Touch took the longest time to build the part at 335 minutes, while the uPrint Plus took less than half the time at 143 minutes. All the systems took slightly longer than their estimated build time with the 3D Touch having the greatest difference of 8 minutes. The systems all provided the volume of material to be used. Using the density of the material, the estimated part mass was calculated. After construction, the part was weighed, with support, to obtain the actual mass. All except one system, the uPrint Plus, estimated a greater amount of material than was necessary. The greatest difference was seen in the SD300 Pro at 13.1 g. Once the support was removed, the part was weighed again to record the mass of the part and the mass of the needed support. The greatest waste in material was seen in the SD300 Pro at 669.8 g, with the actual part only consisting of 7.4% of the total material use. The nature of the sheet lamination technology causes a very high waste in material. It may be more cost efficient to build several parts at once as the amount of material waste will be reduced. The Replicator 2X did not waste any material as no support was needed to build the part. This system also yielded the lightest part at 29.4 g.

Table 6. Build Time and Material Use

System	Estimated Build Time	Actual Build Time	Estimated Part Mass	Actual Part Mass	Support/Waste Material Use	Model Material Use
	min	min	g	g	g	g
SD300 Pro	180	185	735.9	722.8	669.8	53.3
3D Touch	327	335	50.6	47.3	4.2	43.1
Replicator 2X	241	245	32.8	29.4	0	29.4
uPrint Plus	141	143	37.3	39.5	6.4	33.1

Dimensional Accuracy

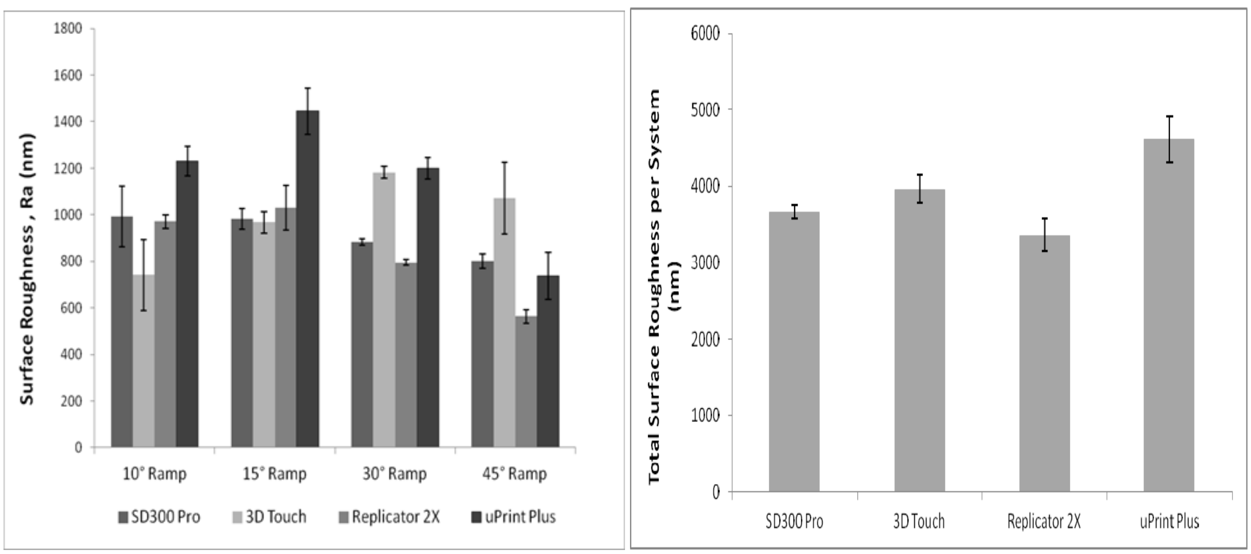
The sum of the dimensional deviations of each system is listed in Table 7. The highest dimensional accuracy was seen in the uPrint Plus, having only 15.37 mm in deviations. The Replicator 2X yielded 23.39 mm in deviations and was followed by the 3D Touch with 36.65 mm in deviations. The lowest dimensional accuracy was the SD300 Pro with a deviation of 57.95 mm. This was an expected occurrence since many of the features broke during the cleaning process and were not measurable on this part. These were therefore, given a dimension value of 0.

Table 7. Sum of Dimensional Deviations of Each System

System	Dimensional Deviation
	mm
SD300 Pro	57.95
3D Touch	36.65
Replicator 2X	23.39
uPrint Plus	15.37

Surface Roughness

Figure 4 (A) illustrates the values of surface roughness obtained from each of four inclined ramps. The Ra value was used for purposes of this experiment and was measured in units of nm. The ramps were built at different angles to evaluate the change in surface roughness with regard to varying inclination. The expectation was for a decrease in ramp angle to increase surface roughness, but this was not necessarily the case. The SD300 Pro was the only system to behave in this manner. The Replicator 2X and the uPrint Plus both had the greatest surface roughness on the 15° ramp. In all but one machine, the 3D Touch, the 45° ramp had the lowest value of surface roughness. The values acquired for each ramp were summed to use one value for the ranking model. These are depicted in Figure 4 (B). The Replicator 2X had the overall lowest surface roughness while the uPrint Plus had the highest. Surface roughness is affected in part by layer thickness. Typically, thinner layers result in less surface roughness. However, the Replicator 2X yielded the lowest value of surface roughness although the part built with the SD300 Pro had the thinnest layers. Measuring surface roughness on an inclined plane versus a flat plane was key as there can be large differences amongst the two. For example, the SD300 Pro's sheet lamination process, which stacks sheet of material on top of one another, yielded a very smooth horizontal surface. However, the ramps were not as smooth because the separation in layers was much more visible.



(A) (B)

Figure 4. (A) Surface roughness with respect to various angles; (B) Total surface roughness per system

Mechanical Testing

Figure 5 shows the results of mechanical testing. Ultimate tensile strength (UTS) was the value input in the ranking model. To attempt the best possible mechanical properties, the test parts were all built as dense as possible. Overall, the uPrint Plus had the highest UTS at 26.8 MPa while the 3D Touch had the lowest value at 20.7 MPa. As previously mentioned, the uPrint Plus has the heated build envelope that helps improve interlayer bonding. This, in turn, can lead to better mechanical properties. The SD300 Pro, which gave the second highest UTS, also has a heated envelope and unlike the other three systems, uses PVC and an adhesive called SolGL-101 to build parts. These may have been factors which contributed to its mechanical properties. The Replicator 2X does not have a heated envelope. However, it does have an enclosed chamber that helps maintain some of the heat dissipated from the build material. The 3D Touch is completely open and the parts rapidly cool to room temperature.

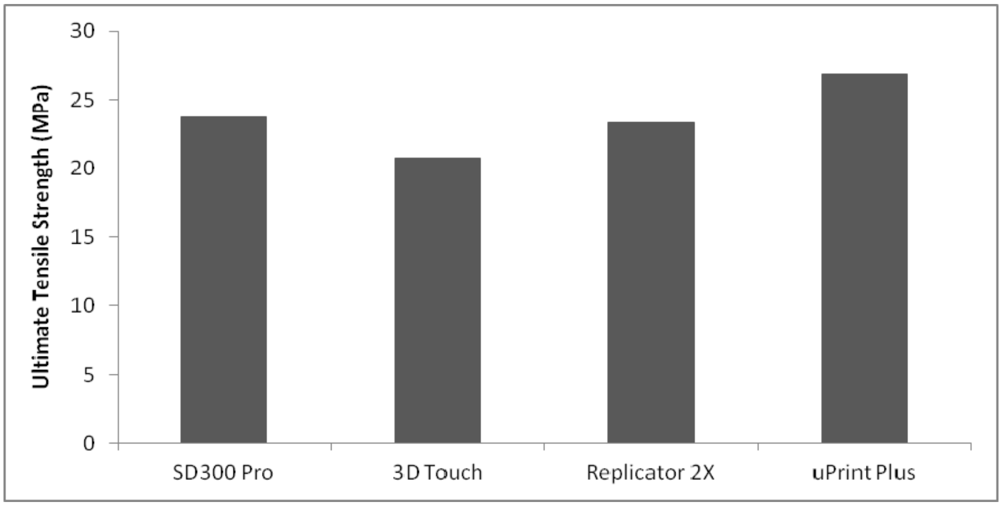


Figure 5. Tensile testing results

Ranking Model

Figure 7 shows how the ranking model was set up. Due to the iterative nature of the ranking model, not all systems received contributions to their final score from all eight factors. This occurred when a system ranked too low in a specific factor to survive all iterations. Values highlighted in gray are those removed after the first iteration. Values in pink were removed after the second iteration. These values received an f(x) value of 0 and did not contribute to the particular system's total score. For these tests, only factors that were of greatest concern to the researchers were included. However, the ranking model can be modified to include more systems or other factors which may be of importance. For example, if system cost is not an issue but system dimensions are, these factors can be substituted.

The results of the ranking model are displayed in Figure 6. Several aspects contributed to these results. For example, the highest score was obtained by the Replicator 2X, which received the highest number of contributions. This system did not receive contributions from two of the eight factors: build time and linear displacement error. The uPrint Plus held the second highest score and did not receive contributions from three factors: system cost, material cost, and surface roughness. This system was largely affected by its cost as well as that of the build material. However, in every other category except surface roughness, it performed well against lower priced systems. It was followed very closely by the SD300 Pro, which also lacked contributions from three factors: part to total material ratio, material cost, and dimensional deviations. Sheet lamination has very high material waste compared to material extrusion, resulting in higher cost to build each part. This affected the SD300 Pro when compared to the other three systems which built much more affordable parts. Finally, the 3D Touch which had the lowest score did not received contributions from four of the eight factors: build time, dimensional deviation, linear displacement error, and tensile testing. Results are very similar to those obtained in Roberson *et al.,* although their test part had simpler features and fewer factors were included in their ranking model [12]. They tested the Replicator, an older version of the Replicator 2X, which also received the highest ranking score. Their results also ranked the uPrint Plus in second place, the SD300 Pro in third, and the 3D Touch in fourth place.

	Build Time, TF (min)			Part/Total Material Ratio, PT			Unit Cost, UC (USD)			Material Cost, MC (USD/part)		
System	x	FC	f(x)	x	FC	f(x)	x	FC	f(x)	x	FC	f(x)
3D Touch	335.00	0.00	0.00	0.91	0.91	0.25	3930.00	0.71	0.23	3.74	0.38	0.14
uPrint Plus	143.00	1.00	0.28	0.84	0.84	0.23	20900.00	0.00	0.00	11.59	0.00	0.00
SD300 Pro	185.00	0.77	0.22	0.07	0.00	0.00	4375.00	0.64	0.20	33.25	0.00	0.00
Replicator 2X	245.00	0.00	0.00	1.00	1.00	0.27	2799.00	1.00	0.32	1.41	1.00	0.36
sum		1.77	0.50		2.75	0.75		2.35	0.75		1.38	0.50
mean, $\bar{x}$	191.00			0.92			3701.33			2.58		
standard deviation, s	51.26			0.08			812.50			1.65		
threshold, ϑ	242.26			0.84			4513.84			4.22		
baseline (min or max)	143.00			1.00			2799.00			1.41		

	Dimensional Deviations, SD (mm)			Surface Roughness, Ra (nm)			Linear Displacement Error, LD (mm)			Tensile Testing, TT (Mpa)		
System	x	FC	f(x)	x	FC	f(x)	x	FC	f(x)	x	FC	f(x)
3D Touch	36.65	0.00	0.00	3961	0.85	0.23	0.02	0.00	0.00	20.74	0.00	0.00
uPrint Plus	15.37	1.00	0.30	4613	0.00	0.00	0.00	0.67	0.20	26.82	1.00	0.27
SD300 Pro	57.95	0.00	0.00	3659	0.92	0.25	0.00	1.00	0.30	23.74	0.89	0.24
Replicator 2X	23.39	0.66	0.20	3360	1.00	0.27	0.02	0.00	0.00	23.36	0.87	0.24
sum		1.66	0.50		2.77	0.75		1.67	0.50		2.76	0.75
mean, $\bar{x}$	19.38			3660			0.00			24.64		
standard deviation, s	5.67			301			0.00			1.90		
threshold, ϑ	25.05			3961			0.00			22.74		
baseline (min or max)	15.37			3360			0.00			26.82		

Removed after 1st iteration

Removed after 2nd iteration

Figure 6. Results obtained via iterative process of ranking model

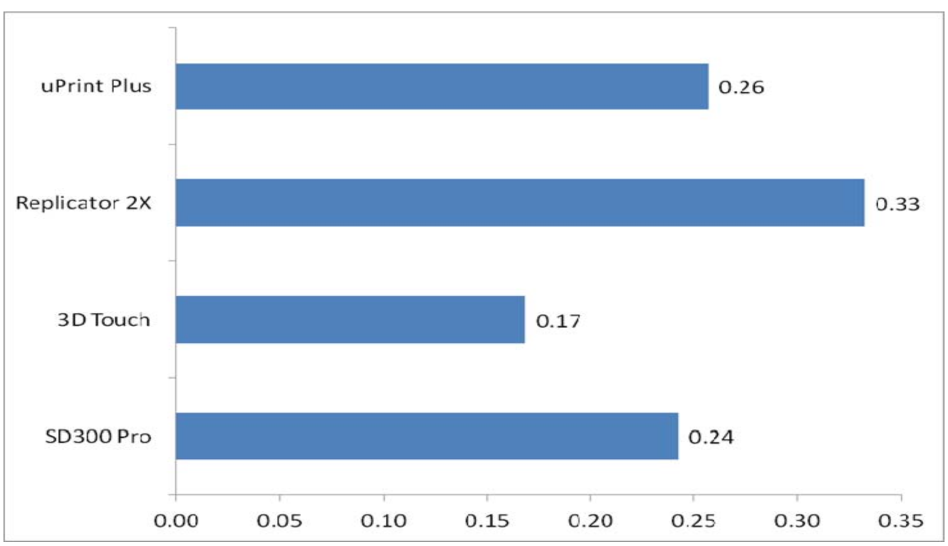


Figure 7. Ranking model results

Conclusion

The current market demand for new and innovative desktop 3D printers has resulted in an influx of new printer designs. There are small affordable systems for the at-home user as well as larger, more expensive systems for the business user. Depending on the use the system is intended for, consumers may have specific requirements. The work presented here focused on using a ranking model with four systems, SD300 Pro, 3D Touch, Replicator 2X, and uPrint Plus based on factors a consumer may consider when purchasing a new system. These included build time, ratio of model material use to total material use, system cost, material cost, dimensional deviations from CAD, surface roughness, linear displacement error, and mechanical properties. For this, a test part was designed that included various geometric features that could be measured to give an idea as to the system's build accuracy. The ranking model found the Replicator 2X to be the best system based on these factors, followed closely by the uPrint Plus and the SD3000 Pro, while the 3D Touch ranked lowest. The ranking model can be easily modified to fit a consumer's preferences.

Future Work

In the future, the authors would like to include more systems in the ranking model. In addition, greater advantage will be taken of the features already integrated into the test part by adding more factors into the ranking model including cylindricity, angularity, and shape factors.

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